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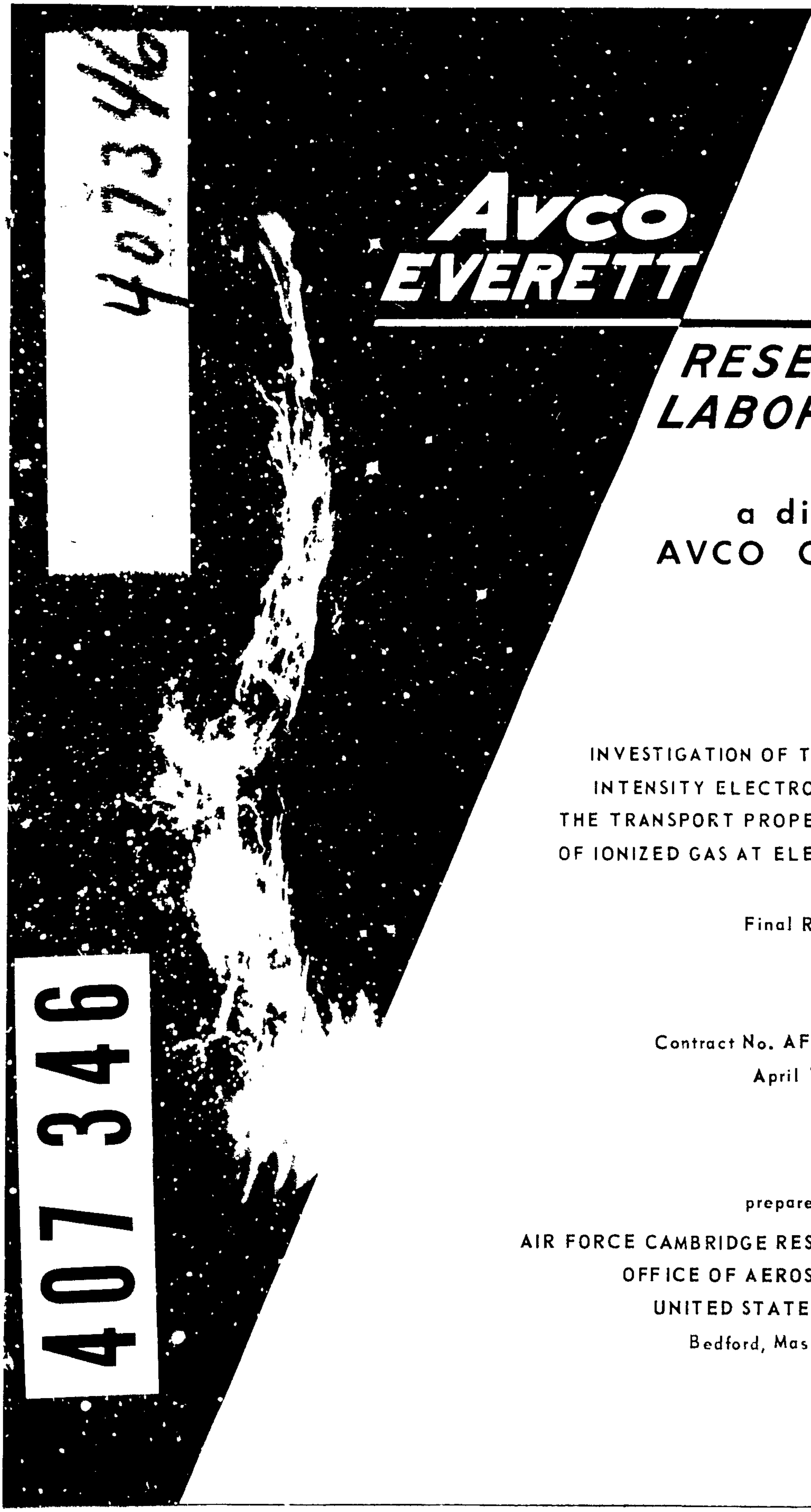

AVCO EVERETT RESEARCH LABORATORY

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INVESTIGATION OF THE EFFECTS OF HIGH INTENSITY ELECTROMAGNETIC WAVES ON THE TRANSPORT PROPERTIES AND PHENOMENA OF IONIZED GAS AT ELEVATED TEMPERATURES

Final Report

Contract No. AF 19(604)-7458
April 1963

prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
Bedford, Massachusetts

AFCRL-63-127

INVESTIGATION OF THE EFFECTS OF HIGH INTENSITY ELECTROMAGNETIC WAVES ON THE TRANSPORT PROPERTIES AND PHENOMENA OF IONIZED GAS AT ELEVATED TEMPERATURES

Final Report

AVCO-EVERETT RESEARCH LABORATORY
a division of
AVCO CORPORATION
Everett, Massachusetts

Project 5561
Task 556112

Contract No. AF 19(604)-7458

April 1963

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ABSTRACT

The research work performed under this contract is briefly summarized and reviewed. A complete list of scientific reports and papers published under this contract is also given.

It is concluded that while much progress has already been made toward fulfillment of all the major scientific objectives, much more remains to be explored and pursued in this field.

TABLE OF CONTENTS

I. OBJECTIVES AND SCOPE OF CONTRACT

The broad scientific objectives and scope of this contract may best be summarized in the original Statement of Work (as revised July 1, 1961), which is reproduced here for convenient reference:

Item 1. - Conduct a theoretical and experimental study of the transport properties and phenomena of ionized gases at elevated temperatures. The investigation shall include, but not (with the exception of the indicated temperature and pressure domain) be limited to, consideration of the following specific topics:

a. Fundamental theoretical studies of the major transport properties including spectral and Planckian radiation emissivity and opacity, thermal and electrical conductivity, viscosity, mass diffusion, thermal diffusion (Soret effect), and diffusion thermo (Dufour effect). The variation and absolute magnitude of these properties and the coefficients associated with the indicated transport processes will be studied at temperatures between 9000 and 25,000°K and at densities ranging from one atmosphere to 10^{-7} atmospheres. The investigations will mainly be directed towards the study of air both at equilibrium and non-equilibrium conditions. From these results, computations of the

various composites dimensionless parameters, such as the Lewis, Prandtl, and Schmidt numbers, will be performed.

b. The coefficients associated with the transport of momentum, thermal energy, radiation and mass (including the electrical parameters) will be determined, insofar as scientifically significant data can be obtained, by application of appropriate experimental techniques. These properties will be determined, wherever possible, throughout the range of pressures and temperatures indicated.

c. The reaction rates behind shock waves leading to the production of such highly ionized gases as required for Item 1b will be determined in order that a known equilibrium state can be obtained.

Item 2 - Conduct an analytical and experimental study to determine the effects of high intensity electromagnetic waves on ionized gases. Such studies will include the following topics:

a. The effect of the radiation on shock wave formation.

b. The effect of the radiation on energy transport and partition within the shock.

c. Alteration of the entropy distribution behind curved shocks.

d. The effect of the radiation on transport properties.

e. The effect of the radiation on the ionization processes within the shock.

f. The general modification of the macroscopic inviscid and viscid flow field due to high intensity radiation.

g. The effect of the radiation on boundary layer characteristics and surface heat transfer.

h. Theories to extend the results to temperatures, densities, RF power levels and frequencies not covered by experiments. Where possible, an attempt will be made to determine characteristic correlations to allow scaling in body size, RF power, RF frequency and altitude.

Item 3 - Provide one (1) electrically-driven shock tube with a sufficiently large test section to permit microwave diagnostics, yet not compromise the required performance specified in Item 1b. The shock tube shall be composed of a driver and test section, dump tank, vacuum system, and all necessary switching networks and leads with the exception of the primary energy source.

II. REVIEW OF PROGRESS AND ACCOMPLISHMENT

The research work carried out under this contract has culminated in 11 scientific reports, 7 published papers, and the successful development of several important scientific instruments and experimental techniques. A list of titles of these reports and papers are given in Section III, and the abstracts from the reports are compiled in Section IV. (The abstracts from the published papers are quite similar to those from the corresponding reports, and are therefore deleted.) A complete set of the scientific reports will be submitted under separate cover as an Addendum to this Final Report.

In addition to the research work mentioned above, several staff members of this Laboratory have also actively participated in various conferences and meetings in support of the Project COMET under the auspices of the Rome Air Development Center, Air Research and Development Command, United States Air Force. A record of this activity can be found in the compilation of Quarterly Status Reports given in Appendix A. Our investigation of the electromagnetically-induced implosion problem, which has excited considerable interest both in Project COMET and in the Jason Division of the Institute for Defense Analyses, is summarized in the classified report, Research Note 255, by S. C. Lin and A. R. Kantrowitz (Report No. 6 listed in Sub-Section III-A).

Even though the major results of the research work performed under this contract have already been fully covered in the scientific

reports and papers just mentioned, we shall, nevertheless, briefly review our progress and accomplishments here. We shall do this according to the ordering of the Scientific Objectives listed in Section I.

Item 1: Theoretical and Experimental Study of Transport Properties and Phenomena of Ionized Gases at Elevated Temperatures.

On the theoretical side, our early survey of the equilibrium chemical composition of high temperature air in the temperature range $9,000 \leq T \leq 25,000^{\circ}K$, and density range $10^{-7} \leq \rho/\rho_o \leq 1$, indicated that the degree of ionization would always be sufficiently high to allow the gas to be treated as being fully ionized. This is illustrated in Fig. 1 and Fig. 2, where the fraction of air molecules ionized [e] and the effective Coulomb cross section Q_i for singly-charged positive ions are plotted respectively as functions of temperature and density. The value of [e] is taken from existing thermodynamic tables,[1-3] and the value of Q_i is calculated according to the theory of Spitzer and Härm.[4-6] It is seen that the product [e] Q_i, which is a measure of the relative collision probability between the electrons and the positive ions in the ionized gas mixture, is of the order of 10^{-14} cm^2 at the lower temperature limit of $9000^{\circ}K$ (taking a median density of 10^{-3} normal atmospheric density). At the upper temperature limit of $25,000^{\circ}K$, the value of [e] Q_i would be about 6×10^{-14} cm^2. Comparing these with the averaged momentum transfer cross section of approximately 10^{-15} cm^2 for the neutral atoms and molecules,[7-9] it is quite clear that electron-ion

collisions will dominate the transport properties in the range of temperature under consideration as soon as the degree of ionization approaches the equilibrium level. Since the theory of linear transport properties in a fully ionized gas was already in a very satisfactory state as a result of the excellent works of Spitzer, et al,[4,5] further work in this area did not appear very profitable. Accordingly, we have directed our theoretical effort in the study of reaction rates behind shock waves leading to the production of ionization in the high temperature gas (Item Ic in Section I). This theoretical effort has resulted in the extensive report, Research Report 115, by S. C. Lin and J. D. Teare (Report No. 10 listed in Sub-Section III-A).

On the experimental side, our effort has been devoted to the development of an electric arc-driven shock tube capable of producing uniform samples of ionized gases in the range of temperature specified for detailed laboratory studies. The development of this unique scientific tool has been very successful, and this shock tube has since been used continuously in this Laboratory for non-equilibrium radiation and heat transfer studies of immediate interest, not only to this contract, but also to other Government agencies such as the National Aeronautics and Space Administration. The development of this electric arc-driven shock tube is fully documented in Research Note 261 by J. C. Camm (Report No. 7 listed in Sub-Section III-A) and in Research Report 136 by J. C. Camm and P. H. Rose (Report No. 9 listed in Sub-Section III-A). Recent scientific results on radiative heat transfer and non-equilibrium radiation from strong shock waves are reported in Research Note 264 by S. Georgiev,

come to an early tentative conclusion that it would generally be quite difficult to produce large thermodynamic and hydrodynamic effects in a gas by intense electromagnetic waves from a distance. One notable exception was, perhaps, electromagnetically-induced implosions as discussed in Research Note 255 by S. C. Lin and A. R. Kantrowitz (Report No. 6 listed in Sub-Section III-A).

Our experimental effort in this area has been concentrated in the development of techniques for producing and observing hydrodynamic effects caused by intense microwave discharges in a one-dimensional channel. This experiment has been quite successful. Even though preliminary results tended to support our tentative conclusion that only relatively weak hydrodynamic effects could be produced in this manner, the techniques did appear promising as a possible means for studying energy transfer mechanisms between free electrons and molecules under typical gas discharge conditions. The theoretical and experimental results from this study have been fully documented in Research Report 138 by S. C. Lin and G. P. Theofilos (Report No. 11 listed in Sub-Section III-A).

Item 3: Provision of One Electrically-Driven Shock Tube for Delivery at the End of this Contract.

The electrically-driven shock tube is ready for delivery at the time of submission of this Final Report.

To sum up the foregoing review, we may say that impressive progress has been made toward fulfillment of all the major scientific objectives listed in Section I. However, in view of the very broad and comprehensive nature of these objectives, which were not unlike those of the scientific community at large working in the general areas of Re-entry Physics, High Temperature Gasdynamics, Kinetic Theory, Gaseous Electronics, Plasma Physics, Chemical Kinetics, Atomic and Molecular Physics, etc., it would indeed be foolhardy to claim that we have fulfilled all the listed scientific objectives within the relatively short span of this contract. We are, therefore, of the opinion that even though much progress has already been made, much remains to be explored in this vast frontier of knowledge.

REFERENCES

1. F . R. Gilmore, "Equilibrium Composition and Thermodynamic Properties of Air to 24,000°K," Rand Corp. RM-1543, August, 1955.

2. J. G. Logan and C. E. Trainor, "Tables of Thermodynamic Properties of Air from 3000°K and 10,000°K at Intervals of 100°K," Cornell Aeronautical Laboratory, Inc., Report No. BE-1007-A-3, January, 1957.

3. J. D. Teare, "Equilibrium Composition of High Temperature Air," Avco-Everett Research Laboratory (Unpublished).

4. L. Spitzer, Jr. and R. Härm, Phys. Rev., 89, 977 (1953).

5. L. Spitzer, Jr., "Physics of Fully Ionized Gases," Interscience, New York, (1956).

6. S. C. Lin, E. L. Resler, Jr. and A. R. Kantrowitz, "J. Appl. Phys., 26, 95 (1955).

7. H. S. W. Massey and E. H. S. Burhop, "Electronic and Ionic Impact Phenomena," Oxford-Clarendon, London (1952).

8. L. Lamb and S. C. Lin, J. Appl. Phys., 28, 754 (1957).

9. S. C. Lin and B. Kivel, Phys. Rev., 114, 1026 (1959).

10. J. M. Wilcox, Rev. Mod. Phys., 31, 1045 (1959).

11. H. Alfvén, Rev. Mod. Phys., 32, 710 (1960).

12. V. V. Fahleson, Phys. Fluids, 4, 123 (1961).

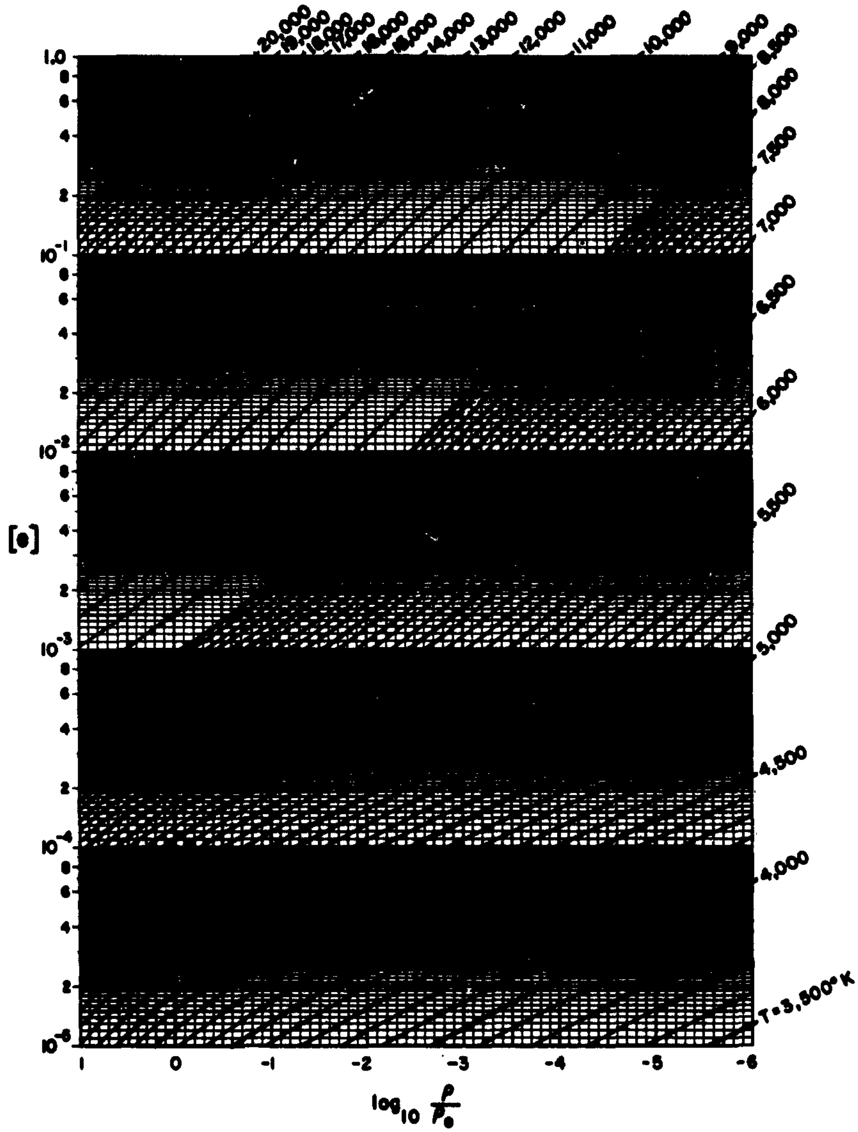

Fig. 1 Equilibrium degree of ionization in air as a function of temperature and density. [e] is the number of free electrons divided by the original number of air molecules. ρ/ρ_0 is the air density divided by the standard sea level air density.

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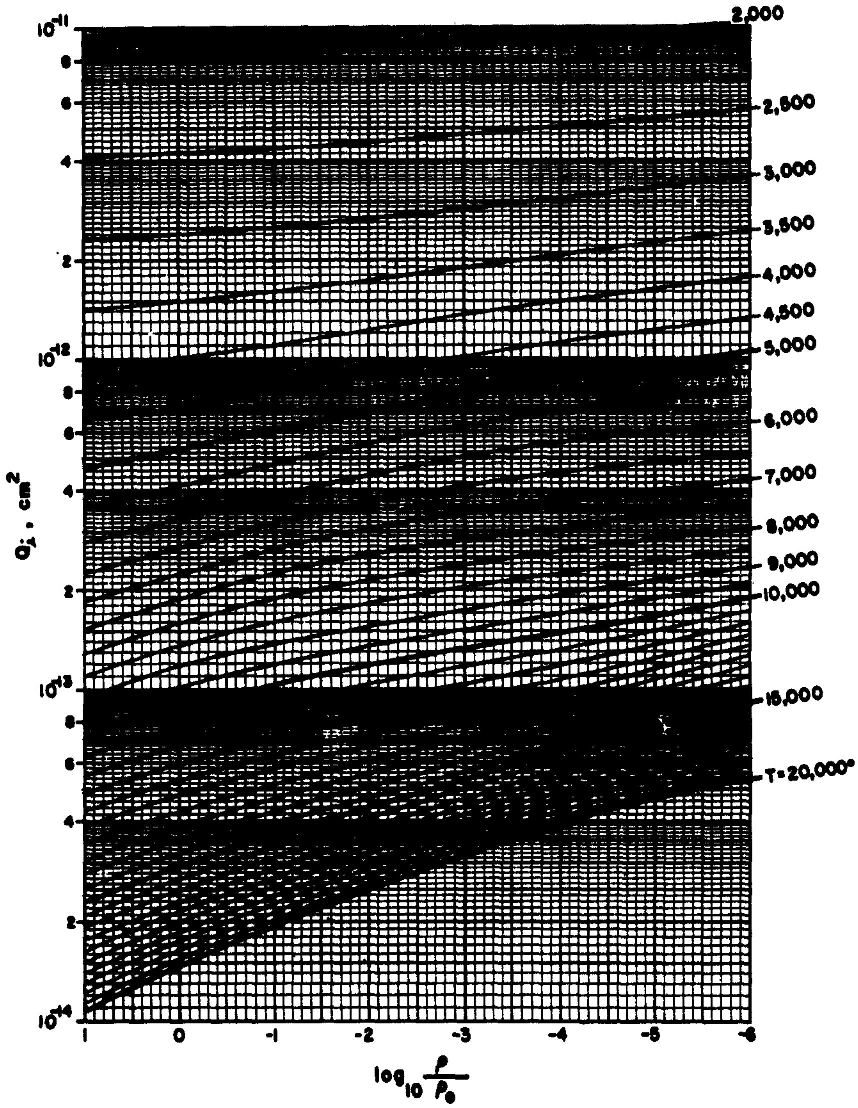

Fig. 2 Effective momentum transfer cross-section for a singly-charged positive ion in an ionized gas mixture with number density of charged particles corresponding to that for equilibrium air at the indicated temperature and density.

9914

III. LIST OF SCIENTIFIC REPORTS AND PAPERS PUBLISHED UNDER THIS CONTRACT

A. Scientific Reports

A list of scientific reports published under this contract is given below in chronological order. A complete set of these reports is to be submitted with this report under separate cover as an addendum:

1. S. C. Lin, "On the Limiting Velocity for a Rotating Plasma," Avco-Everett Research Laboratory Research Report 101, April 1961.

2. S. C. Lin, "A Survey of Shock Tube Research Related to the Aero-physics Problem of Hypersonic Flight," Avco-Everett Research Laboratory AMP 63, July 1961.

3. S. Georgiev, J. D. Teare and R. A. Allen, "Hypervelocity Radiative Heat Transfer," Avco-Everett Research Laboratory Research Note 264, August 1961. (Co-sponsored by Ballistic Systems Division, Air Force Systems Command, United States Air Force, under Contract AF 04(647)-278).

4. M. Camac and R. Feinberg, "The Infrared Heat Transfer Gauge," Avco-Everett Research Laboratory Research Note 265, October 1961. (Co-sponsored by the Air Force Office of Scientific Research, Office of Aerospace Research, United States Air Force, under Contract AF 49(638)-61).

5. J.D. Teare, S. Georgiev and R.A. Allen, "Radiation from the Non-Equilibrium Shock Front," Avco-Everett Research Laboratory Research Report 112, October 1961.

6. S.C. Lin and A.R. Kantrowitz, "Electromagnetically-Induced Implosion," Avco-Everett Research Laboratory Research Note 255, October 1961. (Classified)

7. J.C. Camm, "Escape-Velocity Shock Tube with Arc-Heated Driver," Avco-Everett Research Laboratory Research Note 261, March 1962.

8. M. Camac and R. Feinberg, "High Speed Infrared Bolometer," Avco-Everett Research Laboratory Research Report 120, March 1962. (Co-sponsored by Air Force Office of Scientific Research, Office of Aerospace Research, United States Air Force, under Contract AF 49(638)-1129).

9. J.C. Camm and P.H. Rose, "Electric Shock Tube for High Velocity Simulation," Avco-Everett Research Laboratory Research Report 136, July 1962.

10. S.C. Lin and J.D. Teare, "Rate of Ionization Behind Shock Waves in Air. II. Theoretical Interpretation," Avco-Everett Research Laboratory Research Report 115, September 1962.

11. S.C. Lin and G.P. Theofilos, "Hydrodynamic Effects Produced by Pulse Microwave Discharges," Avco-Everett Research Laboratory Research Report 138, October 1962.

B. Papers Published

The following papers have either been published or accepted for publication in scientific journals and in scientific conference proceedings as of the time of writing of this report. These papers are all related to the scientific reports listed in Sub-Section A above, and are, therefore, attributable to this contract. Additional papers which may be published at a later date with due credit to this contract are not included in this list:

1. S. C. Lin, "Limiting Velocity for a Rotating Plasma," Physics of Fluids, Vol. 4, p. 1277, October 1961.

2. S. C. Lin, "Survey of Shock Tube Research Related to the Aerophysics Problem of Hypersonic Flight," Progress in Astronautics and Rocketry, Vol. 7, ed. by F. Riddell, New York: Academic Press (1962), p. 651.

3. J. D. Teare, S. Georgiev, and R. A. Allen, "Radiation from the Non-Equilibrium Shock Front," Progress in Astronautics and Rocketry, Vol. 7, ed. by F. Riddell, New York: Academic Press (1962), p. 281.

4. M. Camac and R. M. Feinberg, "High Speed Infrared Bolometer," Review of Scientific Instruments, Vol. 33, p. 964, September 1962.

5. S. C. Lin and J. D. Teare, "Rate of Ionization Behind Shock Waves in Air. II. Theoretical Interpretation," Physics of Fluids, Vol. 6, p. 355, March 1963.

6. J. C. Camm and P. H. Rose, "Electric Shock Tube for High Velocity Simulation," (accepted for publication in the Physics of Fluids).

7. S. C. Lin and G. P. Theofilos, "Hydrodynamic Effects Produced by Pulse Microwave Discharges," (accepted for publication in the Physics of Fluids).

IV. ABSTRACTS OF REPORTS

Following are the abstracts of scientific reports published under this contract. A complete set of these reports is to be submitted with this report under separate cover as an Addendum.

RR 101

ON THE LIMITING VELOCITY FOR A ROTATING PLASMA *

Shao-Chi Lin

ABSTRACT

A quasi-steady state solution has been obtained for a homogenous plasma undergoing simultaneous ionization and rotation in a crossed electric-magnetic field. It was found that the ordinary electron-impact ionization process, when supported by the Landau ion-electron heat transfer mechanism, will be sufficiently rapid to provide a close coupling between the kinetic energy of the ions and the ionization energy of the neutrals under a wide range of conditions. The results can be used to interpret the limiting velocity observed by Alfven and Fahleson in some recent rotating plasma experiments. The same results can also be used to predict the occurrence of similar limiting velocity in some rectilinear plasma accelerators.

*Prepared for Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts under Contract AF 19(604)-7458.

AMP 63

A SURVEY OF SHOCK TUBE RESEARCH RELATED TO THE AEROPHYSICS PROBLEM OF HYPERSONIC FLIGHT *

S.C. Lin

ABSTRACT

In recent years, a considerable volume of research has been undertaken in the field of high temperature gas dynamics in which the shock tube has been employed as the principal experimental tool. In particular, a substantial fraction of this research effort has been devoted to the study of phenomena peculiar to air and its component gases, and is, therefore, directly applicable to many aerophysics problems associated with hypersonic flight through the Earth's atmosphere. However, in spite of their omni-existence, most of these works have been published over a period of time in a scattered manner and, hence, appear to be somewhat incoherent.

In the present paper, a preliminary effort is being made to compile these published works under various identifiable (if somewhat arbitrary) topics so as to provide a more convenient reference for investigators in this field. Whenever possible, the advantages and limitations of the shock tube as a research tool for tackling the various topics of interest will also be pointed out.

*Prepared for Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts under Contract AF 19(604)-7458.

RN 264

HYPERVELOCITY RADIATIVE HEAT TRANSFER*

S. Georgiev, J. D. Teare and R. A. Allen

ABSTRACT

For the past several years, extensive theoretical and experimental programs have been carried out for the purpose of establishing the heat transfer to vehicles entering the earth's atmosphere at velocities of up to 25,000 ft/sec. A substantial portion of this effort was devoted to an investigation of the thermal radiation from the heated air behind the strong normal shock associated with the stagnation point region of a blunt re-entry vehicle. Despite the fact that the equilibrium air temperatures in that region are as high as 8,000°K (and non-equilibrium air temperatures near the shock front are as high as 25,000°K) it was found that for most re-entry missions of interest the aerodynamic heating was considerably greater than the radiative heat fluxes emitted by the shock heated air. It was therefore concluded that for re-entry velocities of up to 25,000 ft/sec, the radiative heating does not contribute significantly to the total heating experienced by the re-entry vehicle.

*Supported jointly by Headquarters, Ballistic Systems Division, Air Force Systems Command, United States Air Force, Air Force Unit Post Office, Los Angeles 45, California under Contract AF 04(647)-278 and Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts under Contract AF 19(604)-7458.

This conclusion which was based initially on shock tube experiments has since been substantiated by numerous full-scale ICBM and satellite re-entry flights.

With the advent of space flight missions which involve re-entry velocities in excess of satellite velocity, it is once again necessary to examine the effects of thermal radiation on the heating loads experienced by such re-entry vehicles. The purpose of this paper is to estimate the radiative heat inputs for some typical re-entries associated with return from various space missions, and to discuss the effects of radiative heating on the heat shield performance and design.

RN 265

THE INFRARED HEAT TRANSFER GAUGE*

M. Camac and R. Feinberg

ABSTRACT

A new type of heat transfer gauge that operates in the presence of highly ionized plasmas and in strong electric and magnetic fields has been developed. The principle of its operation is to use a thin opaque surface as the heat transfer element. Aerodynamic and radiative heating is applied to one side of this layer while measurements are made of the change of the infrared emission from the other side. Since the layer is initially at room temperature, the predominant radiation from the surface is in the infrared band from 5 to 30 microns. The opaque layer is made thin enough so that the temperature of the front surface can be determined in less than 0.1 microsecond. This paper describes the components of the heat transfer system and the methods for calibrating the gauge. Measurements are presented of radiative and aerodynamic heat transfer from air with the use of this heat transfer gauge. The infrared heat transfer system has worked successfully in the presence of strong electromagnetic fields; side wall heat transfer measurements have been made on the MAST where the temperature of the hydrogen plasma was in excess of 100,000°K.

*Supported jointly by Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts under Contract AF 19(604)-7458 and Air Force Office of Scientific Research, Office of Aerospace Research, United States Air Force, Washington, D.C., under Contract AF 49(638)-61.

RR 112

RADIATION FROM THE NON-EQUILIBRIUM SHOCK FRONT *

J. D. Teare, S. Georgiev and R. A. Allen

ABSTRACT

Radiative heating of hypersonic objects becomes a significant contributor to the over-all heat transfer at re-entry velocities in excess of 25,000 ft/sec. The radiation from the equilibrium gas cap behind the bow shock wave is in general the major contributor to this heating, but appreciable "luminous front" radiation is also associated with the non-equilibrium region immediately behind strong normal shock waves. The present paper provides a brief review of the published information on radiative heating at 25,000 ft/sec. In addition, the problem of calculating the radiation from the non-equilibrium region at higher velocities is discussed, and some recent experimental measurements for two molecular band systems are presented. Finally, the expected intensity level of non-equilibrium radiation at 35,000 ft/sec is compared with the stagnation point heating caused by radiation from the equilibrium gas and by laminar aerodynamic heat transfer.

*Prepared for Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts under Contract AF 19(604)-7458.

RN 255

ELECTROMAGNETICALLY-INDUCED IMPLOSION*

S. C. Lin and A. R. Kantrowitz

ABSTRACT CLASSIFIED

*Prepared for Electronics Researcl. Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts, under Contract AF 19(604)-7458.

RN 261

ESCAPE-VELOCITY SHOCK TUBE WITH ARC-HEATED DRIVER *

John C. Camm

ABSTRACT

A shock tube has been built which employs arc-heated helium as the driver gas. The helium is heated inside the driver by an arc discharge of 43,000 joules powered by a 264 microfarad capacitor bank charged to 18 KV. The arc current reaches a maximum of 125,000 amperes 25 microseconds after the arc is struck, and the discharge is nine-tenths completed at the end of 40 microseconds. The pressure in the 14 cubic inch driver rises to over 14,000 psi after the discharge and before the diaphragm bursts. The driver will produce shocks with velocities of 37,700 feet per second in a 6-inch shock tube filled with air at a pressure of 50μ of Hg and in a 1-1/2-inch shock tube with air at a pressure of 500μ of Hg. The test time at these velocities is 1 microsecond. Using the same driver conditions, the shock velocity decreases and the test time increases as the initial pressure in the shock tube is increased. The test time is 5μs for a shock having a velocity of 32,800 feet per second in air at a pressure of 100μ of Hg in the 6-inch shock tube. These test times have been verified photographically and by quantitative measurements of the radiation profiles of the shocks.

*Supported by Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force under Contract AF 19(604)-7458.

RR 120

HIGH SPEED INFRARED BOLOMETER *

M. Camac and R. Feinberg

ABSTRACT

A new type of heat transfer gauge that operates in the presence of highly ionized plasmas and in strong electric and magnetic fields has been developed. The principle of its operation is to use a thin opaque surface as the heat transfer element. Aerodynamic and radiative heating is applied to one side of this layer, while measurements are made of the change of the infrared emission from the other side. This system is essentially a bolometer. Since the gauge is initially at room temperature, the predominant radiation from the opaque layer is in the infrared band from 5 to 30 microns. Changes in the temperature of the element are determined by the variation in its infrared emission. The opaque layer is made thin enough so that the temperature of the front surface can be determined in less than 0.1 microsecond. This paper describes the components of the heat transfer system and the methods for calibrating the gauge for heating pulses of long and short duration. The response of the system to a variety of heat pulses has been calculated. Measurements are presented of the aerodynamic heat transfer from shock heated air, and the response time of the gauge to short heat pulses is evaluated. This

*Supported jointly by Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts under Contract AF 19(604)-7458 and Air Force Office of Scientific Research, Office of Aerospace Research, United States Air Force, Washington, D. C. under Contract AF 49(638)-1129.

infrared heat transfer system has worked successfully in the presence of strong electromagnetic fields; side wall heat transfer measurements have been made on the Magnetic Annular Shock Tube where the temperature of the hydrogen plasma was in excess of 100,000°K.

RR 136

ELECTRIC SHOCK TUBE FOR HIGH VELOCITY SIMULATION*

John C. Camm and Peter H. Rose

ABSTRACT

Shock tubes have been developed capable of producing a gas sample of known conditions at velocities as high as 43,000 ft/sec. The driver of these shock tubes employs a capacitor bank which discharges electrical energy into helium, heating the helium to temperatures of 10,000 - 20,000°K, and raising the pressure to 10,000 - 20,000 psi. The high pressure bursts the scribed diaphragm and the resulting shock wave propagates into the test gas.

Extensive diagnostic techniques have been employed in the resulting hot gas samples. The growth of this sample has been observed optically and correlations have been achieved with theoretical calculations. The observed radiation has been compared with and can be used to extend the known radiative properties of high temperature air. Time resolved luminous pictures and spectra have also been taken to show the purity of the test gas. The speed and attenuation of the shock front have been measured.

The observed operation of this shock tube has been compared to theoretical predictions and, although no precise correlation can be made, the driver gas energy transfer and losses in the shock tube boundary layer can be accounted for.

*Prepared for Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts under Contract AF 19(604)-7458.

RR 115

RATE OF IONIZATION BEHIND SHOCK WAVES IN AIR
II. THEORETICAL INTERPRETATION *

S. C. Lin and J. D. Teare

ABSTRACT

The problem of spontaneous ionization (i.e., no externally applied electromagnetic fields, nor hard radiation) in the reaction zone behind strong normal shock waves in air has been treated concurrently with the problem of dissociation and vibrational relaxation. Through a comparison of specific ionization rates, one may conclude that up to a shock velocity of 10 km/sec (about 30 times the speed of sound at room temperature) the predominant electron production process would be atom-atom ionizing collisions. This would be followed in an approximately decreasing order of importance by photoioniza - tion, electron impact, atom-molecule collisions and molecule-molecule collisions. The charge exchange reactions, while not contributing directly to the electron production process, were found to have a small but noticeable indirect effect on the resultant electron density distribution at some distance behind the shock due to their continuous shifting

*Prepared for Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts under Contract AF 19(604)-7458.

of the relative population between atomic and molecular ions (which recombine with the electrons at different rates). The specific rate constants for the atom-atom processes required to interpret all existing experimental results appear to be consistent with a simple extrapolation of the low temperature rate constants according to the crossing-point model of Bates and Massey for atom-atom ionizing collisions.

RR 138

HYDRODYNAMIC EFFECTS PRODUCED BY PULSE MICROWAVE DISCHARGES*

S. C. Lin and G. P. Theofilos

ABSTRACT

An elemtary theory is developed for predicting the strength of pressure waves to be expected from sudden breakdown of a gas by high frequency electromagnetic waves in a one-dimensional geometry. It is shown that for an uncontrolled breakdown where the local field strength is not carefully matched to the instantaneous plasma condition to avoid strong reflections, the heating effect will be self-limiting and the resultant shock strength depends only on the incident wave frequency and on the initial gas density. Numerical example for microwave breakdown in air indicates that at normal sea level density, the shock wave accompanying the breakdown is generally quite weak (of the order of Mach 1.1 at 100 Gc/S frequency). However, for breakdown at lower air densities, stronger shock waves can be anticipated.

Preliminary experimental observations of pressure waves generated in a one-dimensional channel by pulse microwave discharges tended to confirm the general features of the elementary theory but showed somewhat stronger effects than predicted.

*Prepared for Electronics Research Directorate, Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force, Bedford, Massachusetts under Contract AF 19(604)-7458.

APPENDIX A

COMPILATION OF QUARTERLY STATUS REPORTS

INVESTIGATION OF THE EFFECTS OF HIGH INTENSITY ELECTROMAGNETIC WAVES ON THE TRANSPORT PROPERTIES AND PHENOMENA OF IONIZED GAS AT ELEVATED TEMPERATURES

AVCO-EVERETT RESEARCH LABORATORY
2385 Revere Beach Parkway
Everett 49, Massachusetts

a division of
AVCO CORPORATION

STATUS REPORT NO. 1

Contract Number AF 19(604)-7458

November 1, 1960— January 31, 1961

prepared for

ELECTRONICS RESEARCH DIRECTORATE
AIR FORCE RESEARCH DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

ELECTRIC SHOCK TUBE

An electric shock tube driver has been built which produces faster shocks than those produced by conventional combustion shock tube drivers, resulting in an increase in the flight region where stagnation enthalpies may be simulated in shock tubes. The electric shock tube driver consists of a chamber in which helium is heated to a high temperature and pressure by a 30,000 joule arc. The chamber is separated from the shock tube by a diaphragm which ruptures at a pressure of 10,000 psi.

Using the electric shock tube driver and a 1 1/2 inch diameter pyrex shock tube shock speeds of 11 mm/μ sec have been obtained in air at a pressure of 1 mm Hg at a distance of 9 feet from the diaphragm. The test time under these conditions is about 2 μs. The test time was determined from studies of shock luminosity using a drum camera. The drum camera was focused on a 0.5 mm slit placed against the shock tube with the slit perpendicular to the shock tube axis. The result is essentially a snapshot of the shock which shows clearly the good test region, the region where the driver gas is mixed with the test gas, and the driver gas. The radiation profile of the shock was measured using a photomultiplier which sensed the radiation as the shock passed by a point in the shock tube. An oscillogram of the photomultiplier output confirmed the 2 μs test time and showed, in addition, a rapid buildup of radiation at the test point beginning about 10 μs before the arrival of the shock. It is not yet clear whether or not this radiation is from the test gas.

The electric shock tube driver is being attached to a 6" diameter pyrex shock tube. The larger diameter will permit production of shocks in air at lower pressures and should provide longer test times.

SYSTEMATIC EVALUATION TRANSPORT COEFFICIENTS

A gaseous system at high temperature has generally to be considered as made up of three components:

(i) Material particles — molecules, atoms, ions in various internal states of excitation, and electrons;

(ii) Photons of all frequencies $o < \nu < \infty$;

(iii) A general electromagnetic field whose sources are macroscopic charge and current distributions both external and internal.

Correspondingly, the microscopic state of such a system is specified by

(i) A set of molecular distribution functions, one for each kind of particle in a particular internal state;

(ii) Photon distribution functions, and

(iii) The usual Maxwell fields $\vec{E}$, $\vec{B}$, $\vec{D}$, $\vec{H}$.

The behavior of the system is governed by:

(i) A set of particle kinetic equations, one corresponding to each type of particle that may occur in the system;

(ii) A kinetic equation for the photons;

(iii) The Maxwell field equations.

In writing down these equations we have to represent every type of process that may significantly occur in the system; e.g., elastic collisions, inelastic and superelastic collisions, dissociation and combination collisions, emission and absorption of photons, etc.

These equations are sufficiently general to cover a wide range of types of physical situations. However, to construct a mathematically tractable formalism, we have generally to work with macroscopic equations of motion. A great variety of systems of macroscopic equations can be derived from the kinetic equations. The particular such system of equations to be used depends very intimately on the particular physical situation that we wish to consider.

The special physical context determines, in the first place, the particular macroscopic variables to be selected as basic variables, and in the second place, the particular mathematical procedures to be used to reduce the macroscopic moment equations to a determinate set. Thus generalizated and modified versions of the Chapmen-Enskog procedure would, for certain kinds of physical context, provide a systematic derivation of equations of motion and explicit form for all the transport coefficients as functionals of the ways in which the particles interact with one another and with photons. The systematic character of such techniques would ensure that all relevant transport phenomena would be taken into account. In some other cases, n-fluid type equations would be appropriate.

Among the cases of direct physical interest that could be handled in this way we may mention the cases of small departures from local thermodynamic equilibrium: (a) for both matter and radiation, (b) for matter but not for radiation, (c) for matter and for radiation of certain frequencies but not other frequencies.

IONIZATION RATE IN HIGH TEMPERATURE PLASMA

From previous investigations, it was found that the ionization mechanism behind shock waves in diatomic gases (such as air) at ballistic missile and satellite velocities will be mainly controlled by chemical

processes[1,2]. At higher velocities, or when the shock-heated gas is further heated by external means (e.g., externally applied electromagnetic fields), it is expected that other processes, such as electron-impact and photo-ionization, will play increasingly more important roles.

A preliminary theoretical investigation is being made on the electron impact ionization rate in a partially ionized gas in which the electron temperature is controlled by a balance between the ion-electron energy transfer rate and the rate of energy flow into ionization and radiative excitation. (This corresponds to the condition behind strong shocks in the absence of externally applied fields.) The general results from this investigation will also be used to interpret the anomalous results that have been observed by Alfven[3] and Fahleson[4] in some recent rotating plasma experiments.

HEAT TRANSFER MEASUREMENTS

As part of the study of high temperature gases, we are undertaking an experimental investigation of the thermal transport properties. We plan to measure the gas heat transfer to the walls as well as the gas heat content. A novel heat transfer gage that is not sensitive to electric and magnetic fields is being developed. The basic operation of the heat transfer gage is rather simple. A portion of the wall (or stagnation point probe) is coated with a substance that emits in the infrared. The time variation of the temperature of this material is obtained by observing the infrared emission. Radiation from the heat transfer gage is focused with mirrors on a Westinghouse infrared (photoconducting) detector, which is sensitive in the wavelength range from 2 to 9 microns. Observations from objects at room temperature can be made. The heat transfer gage consists of an infrared transmitting material (such as calcium fluoride or sapphire) coated with an 8000 A layer of carbon. The thin layer should reach a uniform temperature in about 2 microseconds.

REPORTS AND PAPERS

No scientific reports have been published and no papers were presented at scientific meetings during this reporting period.

VISITORS TO AERL

Dr. Max Krook, Laboratory Consultant, visited the laboratory to discuss systematic evaluation transport coefficients.

OTHER SIGNIFICANT ACTIONS

Dr. Joseph Hirschfelder of the University of Wisconsin has been invited to visit AERL to discuss transport phenomena in ionized gases.

REFERENCES

1. S. C. Lin, R. A. Neal, and W. I. Fyfe, "Rate of Ionization behind Shock Waves in Air. I. Experimental Results," Avco-Everett Research Laboratory, Research Note 210, September 1960.

2. K. L. Wray, J. D. Teare, B. Kivel and P. Hammerling, "Relaxation Processes and Reaction Rate behind Shock Fronts in Air and Component Gases," Avco-Everett Research Laboratory, Research Report 83 (1959).

3. H. Alfven, Rev. Mod. Phys., 32, 710 (1960).

4. U. V. Fahleson, Phys. Fluids, 4, 123 (1961).

INVESTIGATION OF THE EFFECTS ON HIGH INTENSITY ELECTROMAGNETIC WAVES ON THE TRANSPORT PROPERTIES AND PHENOMENA OF IONIZED GAS AT ELEVATED TEMPERATURES

AVCO-EVERETT RESEARCH LABORATORY
2385 Revere Beach Parkway
Everett 49, Massachusetts

a division of
AVCO CORPORATION

STATUS REPORT NO. 2

Contract Number AF 19(604)-7458

February 1, 1961 - April 30, 1961

prepared for

ELECTRONICS RESEARCH DIRECTORATE
AIR FORCE RESEARCH DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

This report is intended only for internal management uses of the contractor and the Air Force.

ELECTRIC SHOCK TUBE

The electric shock tube driver has been attached to a six-inch diameter pyrex shock tube using an expansion nozzle. Using the six-inch shock tube, shock speeds of 7 mm/μ sec were obtained in air at an initial pressure of 1 mm of Hg and the test time was about 10 μ sec at a distance of 15 feet from the diaphragm. Shock speeds of 10 mm/μ sec were obtained at 0.1 mm of Hg with a test time of about 4 μ sec.

Visible, ultraviolet and infrared radiation measurements are being made on the test gas with particular emphasis being placed on the non-equilibrium phenomena and the precursor radiation, the origin of which has not yet been determined.

An undesirable feature of the present driver design is that the teflon insulator sleeve which runs the length of the arc chamber ablates strongly and deposits a layer of carbon on the inside of the shock tube on every run. Each layer has an optical transmission of about 90%, a fact which makes frequent cleaning of the tube necessary. A search for a more suitable insulating material is being made.

SYSTEMATIC EVALUATION OF TRANSPORT COEFFICIENTS

Systematic evaluation of transport coefficients is being carried out at a relatively slow pace on account of the very generalized nature of this problem. It is to be anticipated that future efforts in this area will be made only at a rate commensurate with the rate of identification of focal points of interest.

IONIZATION RATE IN HIGH TEMPERATURE PLASMA

Our preliminary theoretical investigation on the electron impact ionization rate in a partially ionized gas in which the electron temperature is controlled by a balance between the ion-electron energy transfer rate and the rate of energy flow into ionization and radiative excitation has resulted in the completion of a Research Report entitled "On the Limiting Velocity for a Rotating Plasma" by S. C. Lin, AERL RR-101, April 1961. This will be submitted under separate cover as part of the present status report.

Further investigation in this area may include the effects of high intensity electromagnetic waves on the electron energy balance in such a plasma and of radiative energy transport.

HEAT TRANSFER MEASUREMENTS

Measurements of the total radiation from the shock heated air are being made with the heat transfer gage discussed in the previous report. A portion of the shock tube wall is coated with a thin carbon layer. The

emissivity of the carbon surface is above .9 over the important spectral range (i.e., $\lambda < 10\ \mu$). Thus, the carbon acts as a "black body" and absorbs the radiant energy from the shock heated gas. The variation of the temperature of the carbon surface gives information of the magnitude of the radiation. Estimates of the sensitivity of this apparatus indicate that radiant energies of about 100 watts/cm^3 should be detectable. The instrumentation has been constructed and has been recently installed on the 6 inch electric shock tube.

REPORTS AND PAPERS

The following report has been completed for publication during this reporting period: S. C. Lin, "On the Limiting Velocity for a Rotating Plasma," Avco-Everett Research Laboratory, RR-101, April 1961.

VISITORS TO AERL

Dr. Harry Davis, Assistant Secretary of the Air Force for Research and Development, and Mr. Robert L. Feik, Headquarters, Air Research and Development Command visited the laboratory on April 3, 1961. Various problems in connection with high-power coherent electromagnetic radiation were discussed.

INVESTIGATION OF THE EFFECTS OF HIGH INTENSITY ELECTROMAGNETIC WAVES ON THE TRANSPORT PROPERTIES AND PHENOMENA OF IONIZED GAS AT ELEVATED TEMPERATURES

AVCO-EVERETT RESEARCH LABORATORY
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STATUS REPORT NO. 3

Contract Number AF 19(604)-7458

May 1, 1961 - July 31, 1961

prepared for

ELECTRONICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

ELECTRIC SHOCK TUBE

Search is continuing for a material to replace teflon for the driver liner. Boron nitride is the most promising of the new materials which have been tried.

The precursor radiation mentioned in the last report has been identified as radiation from iron impurities in the driver gas or mixed region scattered by the shock tube walls. Plating the diaphragm with copper failed to diminish the intensity of this radiation, which indicated that the iron was being ablated from the diaphragm while it was opening and not during the electrical discharge. Diaphragms of other materials will be tried.

A mechanical method of initiating the arc has been developed. Initially, one end of a slack starter wire inside the driver is held away from the center electrode by a teflon rod which runs through the center of the electrode. When this rod is released, it is forced into the electrode by the initial 200 lb pressure of the helium driver gas until the starter wire makes electrical contact with the electrode. On the run during which this method was tried a noticeably higher shock velocity was obtained due to the elimination of the energy loss in the lovotron.

Tests are currently being performed to determine the optimum driver chamber length for a given test station and maximum test time.

A new 6-inch electric shock tube that has a 30 ft driven section is being built in accordance with Part I, Paragraph A, Item 3, of the amended Work Statement of this contract dated May 10, 1961. A major difference is that this new tube can be used with capacitor banks up to about 100,000 joules capacity, which is about a factor of two greater than the capacity employed in the present tube. Also, the driver has been designed for a working pressure of 20,000 psi. The new tube is expected to provide greater test time and higher shock velocities than the present tube.

RADIATION FROM HIGH TEMPERATURE AIR

An experimental program is underway on the electric shock tube to study the non-equilibrium and equilibrium radiation from normal shocks in air. Measurements in this shock tube have been made of the equilibrium radiation from nitrogen shocks which overlap measurements taken on combustion driven shock tube. Radiation profiles have been obtained in the visible region of the spectrum and up to 10,000 Å for air shocks up to 37,000 ft/sec.

At lower shock speeds in nitrogen there has been observed a close correlation between the time of peak radiation and the time of peak vibrational temperature. From this it might be inferred that electronic degrees are strongly coupled to vibrational degrees of freedom in the molecule. This hypothesis is further being tested by measuring the integral non-equilibrium radiation and comparing with theoretical estimates based on this assumption.

It is also noticed in air that the time to peak radiation behind the shock is faster than the corresponding time in nitrogen. This could possibly suggest that there is vibrational coupling between nitrogen and oxygen, however, this point is not clear since one would expect chemical rates to proceed faster in the air shock producing the same effect.

HEAT TRANSFER MEASUREMENT

The infrared heat transfer gage, described in the earlier Status Reports, has been used to measure both aerodynamic and radiative heat transfer from high temperature air. For this shock tube application, a portion of the shock tube wall is replaced by a heat transfer gage. A thin layer of carbon of approximately 1000 Å to 8000 Å thick is deposited on sapphire. A gage is made to conform to the shape of the inside surface. Shock-heated gas heats the gage, either by radiation or by thermal contact. It is possible to differentiate between aerodynamic and radiative heat transfer by the following means: Only aerodynamic heat transfer is observed if the carbon layer is overcoated with a layer of highly reflecting aluminum, while both radiation and aerodynamic heating is observed when the carbon layer is exposed to the gas. A direct calibration of the gage was obtained by measuring the heat transfer rates in shock-heated air and comparing these measurements with the experimental results of Rose and Stark (J. Aero. Sci., 25, p. 86, 1958).

Preliminary measurements of the radiation heat transfer rates in shock-heated air have been observed with the use of the plain carbon gages. The carbon gages were placed at the end plate of the shock tube and heated by the air behind the reflected shock. The radiation heat transfer rates increase linearly after the time of arrival of the normal shock for an initial pressure of one cm air and incident shock Mach number of approximately 13. It was observed that the reflected shock-heated gas was in equilibrium and the total radiation was in agreement with the theoretical predictions of Kivel, et al (Annals of Physics, 7, p. 1, 1959; J. Aero. Sci., 28, p. 96, 1961). Efforts are underway to obtain radiation heat transfer at lower pressures and higher shock velocities, especially with the electric shock tube, where incident Mach number of 30 is obtainable at initial gas pressures of 1 mm.

REPORTS AND PAPERS

The following report has been completed during this reporting period:

S. C. Lin, "A Survey of Shock Tube Research Related to the Aerophysics Problem of Hypersonic Flight," Avco-Everett Research Laboratory, AMP 63, July, 1961. (To be presented at the International Hypersonics Conference, sponsored jointly by the American Rocket Society and the Air Force Office of Scientific Research, August 16-18, 1961, at Cambridge, Mass.)

OTHER SIGNIFICANT ACTIVITIES

Drs. Arthur Kantrowitz and S. C. Lin of this Laboratory have been invited to give a talk at the Summer Session of the Institute for Defense Analysis, Jason Division, at Brunswick, Maine, on July 27, 1961. The subject of this talk is described in Part II of this report (Classified Secret).

INVESTIGATION OF THE EFFECTS OF HIGH INTENSITY ELECTROMAGNETIC WAVES ON THE TRANSPORT PROPERTIES AND PHENOMENA OF IONIZED GAS AT ELEVATED TEMPERATURES

AVCO-EVERETT RESEARCH LABORATORY
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a division of
AVCO CORPORATION

STATUS REPORT NO. 4

Contract Number AF 19(604)-7458

August 1, 1961 - October 31, 1961

prepared for

ELECTRONICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

SUMMARY OF PROGRESS

During this reporting period, four technical reports have been completed. These four reports, which cover a major fraction of our research efforts for the first year under this contract in some details, will be submitted under separate covers. Therefore, only the abstracts from these reports are reproduced here on the four pages that follow (see Section IV).

Other Significant Activities

Dr. S. C. Lin of this Laboratory has been invited to present a paper at the 7th Project COMET Meeting at Rome Air Development Center, October 10, 1961. The paper, which was essentially an excerpt of Research Note 255 (see page 5), was well received.

INVESTIGATION OF THE EFFECTS ON HIGH INTENSITY ELECTROMAGNETIC WAVES ON THE TRANSPORT PROPERTIES AND PHENOMENA OF IONIZED GAS AT ELEVATED TEMPERATURES

AVCO-EVERETT RESEARCH LABORATORY
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STATUS REPORT NO. 5

Contract Number AF 19(604)-7458

November 1, 1961 - January 31, 1962

prepared for

ELECTRONICS RESEARCH DIRECTORATE
AIR FORCE RESEARCH DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

ELECTROMAGNETIC INTERACTION STUDIES

An experiment is being set up to study the rate of energy transfer from high intensity electromagnetic waves to a gas under breakdown conditions. This experiment essentially consists of intermittently breaking down a gas at one end of a wave guide, and measuring the hydrodynamic energy in the pressure pulses at the other end of the same wave guide. The electromagnetic breakdown power will be supplied by the rejuvenated APS-20 radar set that was furnished by the Air Force Cambridge Research Laboratory at the beginning of this contract. After considerable rebuilding and modification at the Avco-Everett Research Laboratory, this radar set is now in working order, but is still somewhat erratic in operation due to frequent breakdown of insulations in various parts of the high voltage circuit.

CRITICAL REVIEW OF IONIZATION PROCESSES AND REACTION RATES IN HIGH TEMPERATURE AIR

A critical review is being made on the various ionization processes and the associated reaction rate constants for high temperature air corresponding to conditions of general interest in the ballistic missile and satellite re-entry problems. The results will be presented in the form of a report which deals with a detailed quantitative interpretation of some earlier experimental results which were obtained during the course of performance of a different research contract at this Laboratory.

ELECTRIC SHOCK TUBE DEVELOPMENT

Assembly of the new 120,000-joule arc driven shock tube will be completed within about two weeks. This is the model (or replica model) of the electrically driven shock tube being built for delivery to AFCRL in accordance with Item 3 in the Statement of Work of the present contract. It is anticipated that this new shock tube will also be utilized for continued development and evaluation of the arc-driver principle as well as for the performance of some earlier planned experiments prior to its eventual delivery to AFCRL.

ELECTRONIC HEAT TRANSFER

The infrared heat transfer[1] gauge has been adapted for measuring electronic heat transfer rates. The experimental procedure is identical with that used for the air heat transfer measurements.[1] A 1-1/2 inch diameter chemically driven shock tube is used. Heat transfer measurements from heated argon behind the

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1. Camac, M. and Feinberg, R., "The Infrared Heat Transfer Gauge," Avco-Everett Research Laboratory Research Note 265, Oct. 1961.

reflected shock is made with the carbon gauge mounted at the center of the end plate. The initial pressure was 1 mm Hg and incident shock velocities were from 4.5 mm/μsec to 6 mm/μsec. For these conditions the degree of ionization of the argon ranged from 30 percent to 60 percent. It has been shown theoretically[2] that for these conditions, electronic heat transfer will dominate over A_r and A_r^+ heat transfer rates. The experimental measurements are in general agreement with theoretical predictions.[2]

REPORTS AND PAPERS

No scientific reports have been published during this reporting period, but some are under preparation.

OTHER SIGNIFICANT ACTIONS

Dr. S. C. Lin of this Laboratory was invited to attend the last RADC Radiation Committee Meeting on January 22 and 23, 1962, at New York University, University Heights, N.Y. He was asked to be guest speaker for the first day of the two-day meeting, mainly to review the material presented in Avco-Everett Research Note 255 (See Status Report No. 4, August 1, 1961-October 31, 1961), and to participate in subsequent discussions.

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2. Kemp, N., Avco-Everett Research Laboratory, Private Communication.

INVESTIGATION OF THE EFFECTS ON HIGH INTENSITY ELECTROMAGNETIC WAVES ON THE TRANSPORT PROPERTIES AND PHENOMENA OF IONIZED GAS AT ELEVATED TEMPERATURES

AVCO-EVERETT RESEARCH LABORATORY
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a division of

AVCO CORPORATION

STATUS REPORT NO. 6

Contract Number AF 19(604)-7458

February 1, 1962 - April 30, 1962

prepared for

ELECTRONICS RESEARCH DIRECTORATE
AIR FORCE RESEARCH DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

ELECTRIC SHOCK TUBE

The new 6-inch diameter 30-foot arc-driven shock tube has been completed. Initial runs using 64 percent of rated capacitor bank energy have produced shocks with velocities of 1.3 cm/μ sec (42,700 ft/sec) in air at a pressure of 0.1 mm of Hg.

Efforts are being made to find an inorganic driver liner more suitable than the teflon currently being used. Preliminary tests show that use of a bonded fiberglas liner results in a 10 percent increase in shock speed where tested and that liner ablation is markedly reduced.

The shock tube is currently being used to measure the electronic heat transfer rate at the stagnation point of blunt models using shocks that simulate re-entry at speeds greater than 30,000 ft per second. Standard calorimeter gages are used at the stagnation point and these are coated with a 1000-Angstrom evaporated film of SiO to insulate the gage from spurious electrical effects due to gas ionization and photo-electric effects.

A paper describing the shock tube and its performance entitled "Escape Velocity Shock Tube with Arc-heated Driver," was presented at the Second Symposium on Hypervelocity Techniques at the University of Denver.

MODIFICATION OF THE A.P.S.-20 RADAR AND THE R.F. GENERATED SHOCK WAVE EXPERIMENT

The A.P.S.-20 radar unit, after eliminating the receiver section, was set up. The experiment involved using the radar as a means to obtain high r.f. power from the QK-624 magnetron. The units employed consisted of transmitter, modulator, power transformer assembly, and control unit. The transmitter received was defective in that the secondary of the high voltage pulse transformer was open. This has subsequently been rewound by A.F.C.R.L. and installed back into the transmitter.

The modulator unit was in excellent working condition. The time required for installation and modification of this unit was slight. Because of its age, however, this unit needed new reverse current diodes and charging diodes.

Most of the work was primarily involved in redesigning and modifying the control unit. The circuits for automatic high voltage control were replaced with a manual control. The general layout of plugs had to be redesigned and new connections made. This afforded a better method to control the transformer assembly and subsequently the high voltage.

Magnetron installation involved designing a mount and an oil container for the high voltage electrodes. In conjunction with waveguide positioning, a metal holder was designed and built which was attached to the magnetron mount.

Since the experiment involved intentional breakdown, the magnetron, which can withstand a maximum standing wave ratio of 1.3 under steady arcing condition, was protected with a circulator dissipating all the power that was reflected from the breakdown region.

R.F. monitoring of the incident and reflected power was accomplished by a cross-guide directional coupler. Inserted in the output of the waveguide, it monitors both reflected and incident power. Attenuators of large values were inserted to decrease the high peak power to useable value for crystal and balometer measurements. The crystals were calibrated with a water load and the balometer measurements checked with the water load. The pulse width and repetition rate were measured with a Tektronic scope (with a wide band pre-amplifier).

The heater circuit was redesigned to insure that the radar was not turned on with the heaters at maximum current surge. Heaters melting would be a natural outcome of turning on the radar with the heaters on. A manual control and a meter were installed to insure that the heaters were turned up voltage-wise, slowly. (A stop was also installed to limit the voltage to maximum of 3.60 volts.)

The maximum power output measured with the water load was 600 kilowatts peak and 280 watts average. The pulse width, measured at "half altitude" points, was 2.5 μsec. The repetition rate 200 pulses per second

The next phase of the experiment was the designing and building of a primative R.F. driven shock tube. The experiment dictated that the R.F. energy be as close as possible to energy transferred in a traveling wave. A lucite tube of the same internal cross-section as the wave guide was mounted in a standard gain horn. The standard gain horn allowed the power to radiate into space with a minimum amount of reflection.

Holes were drilled along the lucite section for mounting a Kistler pressure transducer for shock velocity as well as for pressure rise measurements. Each hole was equally spaced from the other. The unit in general offered little back reflections of R.F. power.

At the end of the hydrodynamic lucite shock tube a large dump tank was mated. The hydrodynamic wave dissipated itself in it. No reflections were evident in the pressure sensing device. The dump

tank, which was connected to the lucite section, was pumped down by a vacuum pump. The pressure was monitored by a N.R.C. Alphatron gage and varied by a metering valve at the inlet to the system.

Preliminary results indicated that the shock wave generated by an r.f. pulse of 230 kw peak power for 2.5 μsec in air at an initial pressure of 600 mm Hg was of the order of Mach 1.08. Preliminary pressure indication at the sensor (pressure transducer) was of the order of .25 psi. The apparent discrepancy between the shock speed measurement and the pressure rise measurement was probably due to the poor frequency response of the pressure transducer, as well as due to the limited accuracy of the shock velocity measurement.

CRITICAL REVIEW OF IONIZATION PROCESSES AND REACTION RATES IN HIGH TEMPERATURE AIR

This work is still in progress. Publication of the final report, however, would have to wait until all the crucial numerical computations are completed.

REPORTS AND PAPERS

No scientific report has been published during this reporting period, but some are under preparation.

INVESTIGATION OF THE EFFECTS OF HIGH INTENSITY ELECTROMAGNETIC WAVES ON THE TRANSPORT PROPERTIES AND PHENOMENA OF IONIZED GAS AT ELEVATED TEMPERATURES

AVCO-EVERETT RESEARCH LABORATORY
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a division of

AVCO CORPORATION

STATUS REPORT NO. 7

Contract Number AF 19(604)-7458

May 1, 1962 - July 31, 1962

prepared for

ELECTRONICS RESEARCH DIRECTORATE
AIR FORCE RESEARCH DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

ELECTRIC SHOCK TUBE

The new 6-inch diameter 30-foot arc-driven shock tube has been in operation for almost five months. An initial paper describing the shock tube (RN 261) was presented at the Second Symposium on Hypervelocity Techniques at the University of Denver. A revised version of this paper, which includes the experience gained in the operation of this tube over the past few months, has been completed and is being submitted to the Physics of Fluids. An abstract of this paper is attached herewith.

Efforts are continuing to improve this type of shock tube, particularly the driver where most of the losses appear to occur. Currently, insulating liner materials other than the teflon now used are under investigation as well as a segmented metallic wall driver.

The prime experiment performed in this shock tube has been the measurement of electronic heat transfer at simulated stagnation conditions up to 45,000 ft/sec. Standard calorimeter gages coated by a thin layer of SiO to insulate the gage from the conducting ionized gas have been used. The data accumulated has disagreed with the strong effects due to electron conductivity which has been published by other investigators.

R. F. GENERATED SHOCK WAVE EXPERIMENT

The R. F. Generated Shock Wave Experiment described in the last Quarterly Status Report has been extended to cover a range of initial pressure $300 \leq p_1 \leq 740$ mm. Hg. and a corresponding range of peak R. F. power $80 \leq P_{peak} \leq 470$ kw. The lower limit of initial pressure was dictated by the limited sensitivity of the pressure transducer employed for shock velocity and pressure rise measurements, while the upper limit of initial pressure was dictated by the power handling capacity of the pressurized waveguide system which connects the magnetron to the shock tube, in the presence of strong R. F. reflection from the breakdown region in the shock tube.

The shock strength produced under these conditions appeared to lie in the range $1.03 \leq M_1 \leq 1.09$, which is in approximate agreement with theoretical prediction. However, the breakdown power density corresponding to each initial pressure appeared to be somewhat lower than predicted.

A final report on this experiment is currently under preparation.

CRITICAL REVIEW OF IONIZATION PROCESSES AND REACTION RATES IN HIGH TEMPERATURE AIR

The crucial numerical computations related to this work as mentioned in the last Quarterly Status Report are almost completed. A final

report on this work is under preparation. This will be published as a theoretical paper which explains in detail some earlier experimental works performed in this Laboratory under a separate contract.

REPORTS AND PAPERS

During this reporting period, one scientific paper has been presented to the American Physical Society Summer Meeting, and two Research Reports have been published. The Abstracts of these are reproduced on the pages that follow. (see Section IV).

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